The Birth of the First Quasars

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The existence of billion-solar-mass-black holes in massive galaxies less than a billion years after the Big Bang poses one of the greatest challenges to the current paradigm of cosmological structure formation, mostly because it is not understood how they became so massive so early in the universe. Early structure formation is thought to be hierarchical, with small objects at early times evolving into ever more massive ones by accretion and mergers through cosmic time.

It is generally supposed that the supermassive black holes (SMBH) that power the Sloan Digital Sky Survey quasars grew from much smaller seeds at earlier epochs. The origin of SMBHs is of ongoing debate, and three formation channels have been proposed for their seeds: 1) the collapse of primordial stars into 100–300 solar mass black holes 200 million years after the Big Bang, 2) the direct collapse of 10^8 solar mass protogalaxies that have somehow bypassed previous star formation into 10^4–10^6 solar mass black holes about 600 million years after the Big Bang, and 3) more speculative pathways like the relativistic collapse of dense primeval star clusters into 10^4–10^6 solar mass black holes.

The processes by which black holes (BH) form at high redshift and later become supermassive must explain how they become so large just 800 million years after the Big Bang and why their numbers are so small–about one per billion cubic light-years. Although BH-BH mergers likely play a role in SMBH assembly, only accretion can result in the sustained exponential growth required for high-redshift seeds to become supermassive by the time the universe becomes fully ionized at about 1 billion years. Simple Bondi-Hoyle accretion is often invoked to model their growth:

$$\dot{M}_{BH} = \frac{4\pi\rho_\infty G^2 M_{BH}^2}{c_\infty^2 + v_{rel}^2}$$

where ρ_∞ and c_∞ are the density and sound speed of the flow in the vicinity of the BH and v_{rel} is the velocity of the BH relative to the local flow. Because accretion rates depend strongly on mass, seed BHs that form by direct collapse initially grow much faster than primordial (Pop III) BHs, but they form at much lower redshifts and have less time to accrete before reionization is complete.

We are using the Enzo adaptive mesh refinement (AMR) cosmology code to model the collapse of z ~ 10–15 protogalaxies into supermassive BH seeds. The process begins when low-mass cosmological halos (spheroidal blobs of dark matter and primordial gas) gravitationally congregate into a small, highly irregular protogalaxy from z ~ 15–30. For an SMBH seed to form at the center of this primitive galaxy, none of its constituent halos can previously have hosted star formation because such stars would have evicted all the gas from their halos and the protogalaxy would have been born bereft of gas. The only way this can happen is if the protogalaxy is assembled in close proximity to very strong ultraviolet (UV) sources that sterilize the halos of molecular hydrogen and quench star formation. Such UV backgrounds are thought to be highly unusual in this era, which could explain why SMBHs are rare at z ~ 6.

The protogalaxy is hot after it has formed because the kinetic energy its halos once had is converted into heat when they become bound together. Its gas begins to cool by exciting hydrogen (H) and helium (He) line emission, and it pools in the deep gravitational well at the center of the galaxy. Infall rates there become enormous, 0.1–1 solar masses per year, and a stiff hydrostatic core of gas soon forms that rapidly reaches 1000 solar masses or more. At this point it is not known if this object achieves nuclear burning or remains a hot, dead, entropic ball of gas that is later enveloped by an event horizon without ever having become a star. Numerical simulations performed to date to resolve this hydrostatic

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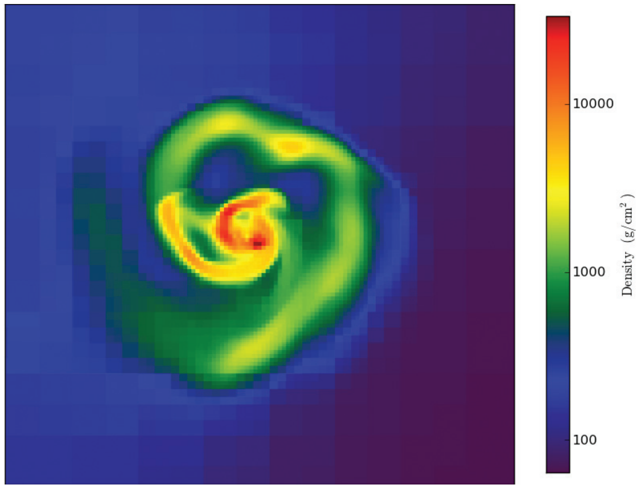

Fig. 1. Formation of an accretion disk around a supermassive star in a collapsing protogalaxy at redshift z = 15.4. The box size is 2000 AU by 2000 AU.

core stall because their time steps become very small and the calculation halts.

We have performed new calculations that prove that if this stiff hydrostatic core of gas does become a massive star, its radiation is always confined close to its surface by the enormous accretion flows raining down on it and cannot propagate out into the galaxy. This result implies that it is not necessary to resolve the hydrostatic seed, just the inflows onto it on larger scales. Retreating from the extreme spatial resolutions previously applied to the seed while preserving the fidelity of the calculation allows us to take much longer time steps in the numerical simulations and evolve the center of the collapsing protogalaxy over many dynamical times. This in turn enables us to determine if infall onto the nascent supermassive star collapses into an accretion disk around it and, later, the conditions under which X-rays from the newborn BH break out into the intergalactic medium after the star dies.

We show Enzo simulations that follow the internal collapse of the protogalaxy in Figs. 1 and 2. They reveal that a massive, atomically cooled accretion disk does form around the central object and rapidly feeds its growth. In parallel with these numerical models, we are pursuing detailed stellar evolution calculations of the fate of the central object with the KEPLER code with Alexander Heger at the University of Minnesota. These simulations will reveal if the object at the center of the disk becomes a star and at what point it becomes a BH. This in turn tells us for how long we must evolve the disk at the heart of the protogalaxy and when we must turn on X-ray emission from the newly formed SMBH seed. These state-of-the-art calculations together with LANL expertise in radiation transport may soon allow us to witness the birth of the first quasars in the universe with supercomputers.

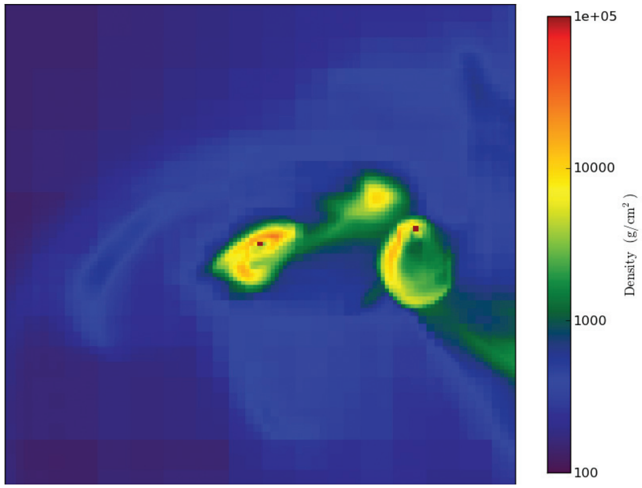

Fig. 2. Fragmentation of the disk into several supermassive Pop III stars.

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